Characterizing Storm-Induced Dune Erosion: Implications to Coastal Modeling

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Key Points:

- Observations are used to quantify the accuracy of assumptions used in dune erosion models.
- Dune vulnerability to overwash is observed to increase due to dune erosion.
- Initial beach width, dune volume, and wave-impact hours contribute to dune erosion variability.

Abstract

Models of dune erosion depend on a set of assumptions that dictate the predicted evolution of dunes throughout the duration of a storm. Assumptions include defining parameters based on laboratory experiments and limited field observations. Lidar observations made before and after Hurricane Sandy at over 800 profiles are used to quantify specific dune erosion model parameters including the dune face slope, which controls dune avalanching, and the trajectory of the dune toe, which controls dune migration. Observed dune face slopes steepened by 43% yet

What is meant by "trajectory"?

did not become vertical faces, as is often assumed and only 50% of the dunes evolved at a trajectory similar to the foreshore beach slope. Observations indicate that dune crests were lowered, a metric not historically used to validate wave-impact dune erosion models. The analysis shows an increased elevation loss at locations with narrower beaches, smaller dune volumes, and/or longer wave-impact.

1 Introduction

Dunes along sandy coastlines provide a buffer between storm-induced water levels and back barrier ecosystems and infrastructure. However, when storms cause the total water level (TWL), comprised of astronomical tides, wind surge, and wave runup, to increase above an elevation between the dune toe and dune crest [*Sallenger*, 2000], erosion occurs and the protective capability can be reduced. Dune erosion often results in the landward recession of the dune base, offshore transport of dune sediments to nearshore sand bars, and avalanching/slumping of the dune face [*de Winter* et al., 2015; *Larson* et al., 2004; *Masselink and van Heteren*, 2014; *Schubert* et al., 2015; *van Gent* et al., 2008; *van Rijn*, 2009]. With the expected rise of sea-level [*Rhein and Rintoul*, 2013] and potential increase in storm intensity [*Grossmann and Granger Morgan*, 2011; *Keim* et al., 2004], wind and wave-driven water levels could impact coastal dunes more frequently and for longer durations, hence, tools to predict morphologic changes during all types of storms (e.g. extratropical and tropical storms) will be increasingly important. Here, we characterize the dune morphology before and after Hurricane Sandy using observations over a wide geographic area. Analysis of the data is performed in order to test and quantify certain parameters that are currently used in dune erosion models (e.g. Fisher and Overton [1984], Larson et al. [2004] and Palmsten and Holman [2012]).

Is the observation area gemorphically diverse or similar?

A range of modeling techniques have been developed to simulate dune erosion including simple relationships between forcing parameters (e.g. wave height or water level), local morphology, and observed dune response [*Long* et al., 2014; *Sallenger*, 2000; *Stockdon* et al., 2007], wave-impact models that relate the eroded volume to the force associated with wave-impact [e.g. *Erickson* et al., 2007; *Larson* et al., 2004; *Larson* et al., 1990; *Palmsten and Holman*, 2012], and more complex models that explicitly compute interactions between waves, currents and sediment transport [*Roelvink* et al., 2009; *Splinter and Palmsten*, 2012]. Here we focus primarily on wave-impact models which were developed to predict dune erosion processes (rather than overwash or flooding). They are computationally efficient and can compute a time sequence of the erosion process but rely on a set of a priori assumptions about how dunes will evolve. However, we note that the parameters we assess can also be used to inform other types of modeling approaches.

Existing wave-impact models [e.g. *Larson* et al., 2004; *Palmsten and Holman*, 2012; *Splinter and Palmsten*, 2012] simulate the storm-induced landward dune migration by specifying a constant trajectory for the dune toe that is tied to the pre-storm foreshore beach slope. At each time step, as the dune toe migrates along the pre-defined slope, a sediment volume to be removed from the dune is computed based on wave forces. This volume is subtracted from the previous dune profile, assuming the new dune profile will have a vertical front face and a dune toe that migrates landward and increases in elevation following the upward-sloping foreshore beach. The validation for these models has traditionally focused on predicting the position and elevation of the dune toe without consideration of the dune face slope or potential changes in elevation of the dune crest. While the assumptions currently used may be valid for the locations used in model development, typically higher bluff-like features, additional data over broad regions are used here to test these constraints in other dune environments.

Many dunes along the U.S. Atlantic coast were eroded during Hurricane Sandy in 2012 [*Sopkin* et al., 2014]. Large data collection efforts were made before and after the storm to quantify the magnitude of coastal change. Data from undeveloped regions in three states have been used to extract dune morphology at over 800 locations focusing on testing model assumptions of the trajectory of the dune toe and the eroding slope of the dune face. Uncertainty in these model parameters is also addressed by identifying variability in the observations.

If the environments are different, won't the transect spacing "weight" the results unevenly?

2 Hurricane Sandy

Hurricane Sandy impacted a large swath of the U.S. Atlantic coastline, causing widespread dune erosion across multiple states. The storm reached category 3 strength on the Saffir-Simpson scale, but weakened to a tropical storm before making landfall near Brigantine, New Jersey on October 29, 2012 [*Blake* et al., 2013]. Storm-induced coastal change was quantified over the entire region using pre- and post-storm elevation data collected with airborne lidar [*Sopkin* et al., 2014]. Impacted dunes at locations with minimal anthropogenic infrastructure were used for this study (Figure 1), including locations on Assateague Island, Maryland, state parks and uninhabited islands in New Jersey, and areas of Fire Island, New York. Assateague Island had the lowest pre-storm dune elevations of the study region (3.6 m mean dune crest elevation), but also experienced the lowest average surge (1.4 m) and wave height (6.1 m). The largest average pre-storm dune crest elevation was located in New Jersey (6.5 m); however, this region also experienced the largest surge (2.2 m) and wave height (8 m).

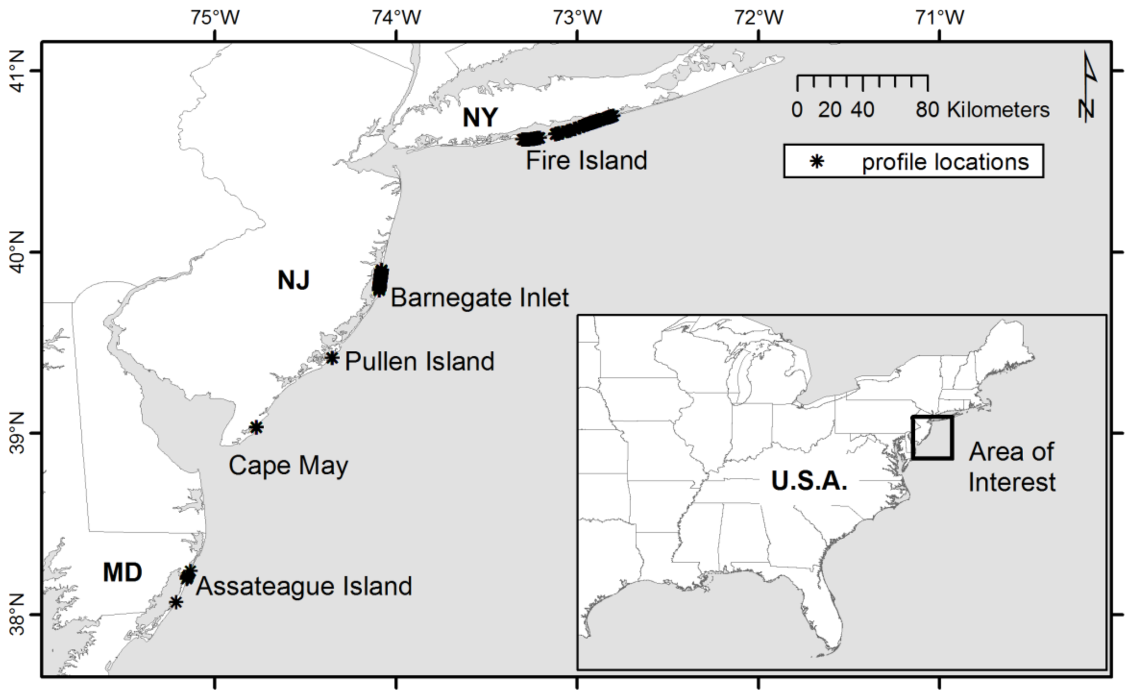


Figure 1. Alongshore locations of selected dunes in undeveloped regions of Maryland, New Jersey, and New York.

3 Methods

The predicted maximum TWL above the dune crest ($TWL - Z_c$), defined as dune freeboard, F (definition consistent with Long et al. [2014]) was used to identify beach profiles expected to experience dune erosion (i.e. collision; $Z_c >$ TWL $> Z_t$; negative F) rather than overwash (TWL $> Z_c$; positive F) according to the storm-impact scaling model of Sallenger [2000]; where Z_C and Z_T are the elevations of dune crest and toe, respectively. Here we focus on the 861 cross-shore profiles in the study region that were predicted to experience only dune erosion.

3.1 Dune morphology

“were”

Lidar data was interpolated to shore-parallel grids with 10-m and 2.5-m spacing in the alongshore and cross-shore directions, respectively. At each cross-shore profile, characteristics that define the shape and seaward/landward extent of the pre- and post-storm dune features are extracted [*Sopkin* et al., 2014; *Stockdon* et al., 2009; *Stockdon* et al., 2012] including the dune crest and dune toe elevations, beach slope, dune volume, dune heel, and dune face slope. Using a full range of dune characteristics we test existing model parameters (e.g. dune toe trajectory) and examine alongshore variability. The observed pre- and post-storm dune toe positions and elevation are used to calculate a trajectory of the dune toe (θ_T), which is compared to the foreshore beach slope (β_f). Existing wave-impact dune erosion models assume a dune toe trajectory either equal to [*Erickson* et al., 2007; *Larson* et al., 2004; *Splinter and Palmsten*, 2012] or roughly half of β_f [*Palmsten and Holman*, 2012]. The slope between the pre-storm dune toe and dune heel, θ_H, is also computed as an alternate approach.

Is dune toe trajectory simply an angle?

Is dune toe trajectory simply an angle?

The dune heel is defined as the inland extent of the primary dune feature, essentially the dune toe on the landward extent of the dune, similar to that used by Judge et al. [2003]. Similar to identifying the dune toe, the dune heel was chosen by an automated algorithm as the point of greatest curvature, landward of the dune crest. All transects were visually checked and misidentifications were manually edited. Dune volumes, V_D, were calculated between the cross-shore location of the pre-storm dune toe, and pre-storm dune heel. The profile was integrated between these features using a baseline at either the elevation of the pre-storm dune toe or dune heel, whichever was lower. The cross-shore varying slope of the seaward dune face was computed on each profile using a central finite-difference applied at each point between the locations of the dune toe and crest. The maximum slope on each dune face was selected as the representative dune slope, β_D. Finally the integrated time that the TWL time series exceeded the elevation of the dune toe, ($\sum t(TWL > Z_T)$; e.g. wave-impact hours) is also calculated to explore variability in the dune response at different profiles.

3.2 Predicted Total Water Level

The maximum TWL along the coast was estimated by adding the 2% exceedance probability of wave runup, $R_{2\%}$ to modeled water levels that include wind surge and tide (η). Wave runup is calculated using the empirical relationship of Stockdon et al. [2006]:

$$R_{2\%} = 1.1\left(0.35\beta_f (H_0 L_0)^{\frac{1}{2}} + \frac{\left[H_0 L_0\left(0.563\beta_f^2 + 0.004\right)\right]^{\frac{1}{2}}}{2}\right), \quad (1)$$

where the first term in parentheses represents the wave setup and the second is the wave swash. In this formulation, H_0 is the significant deep water wave height and L_0 is the deep water wave length, which depends on wave period T_0. The H_0 and L_0 were estimated with output from a hindcast simulation of Hurricane Sandy using the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system [*U.S. Geological Survey*, 2016; *Warner* et al., 2010; *Warner* et al., 2008]. Time-series of modeled H_0, T_0, and η were interpolated to the 20-m contour. Orthogonal lines between the 20-m contour and the shoreline were used to connect the storm hydrodynamics to the shoreline at each profile location. Surge and tide levels were extracted at the 20-m contour rather than the shoreline to ensure minimal influences from the shoreline model boundary, which was not well resolved.

Does this assume that there will be standard Airy wave transformation (shoaling and refraction) to the 20-m isobath?

4 Results

Personal pet peave = “flattened” doesn’t necessarily mean “less steep”, but rather “more planar”

Contrary to typical model assumptions, dune face slopes both steepened (Figure 2a-c) and flattened (Figure 2d) as result of Hurricane Sandy, and the dune toe trajectory sloped both positively (Figure 2b-c) and negatively (Figure 2a) relative to the cross-shore reference system (i.e. sometimes in the opposite direction of the foreshore beach slope). Although each of the profiles used in this analysis were expected to be in the collision regime ($F < 0$ and $TWL > Z_t$) and undergo dune erosion during the storm, some of the observed profile change appeared to be the result of overwash based on the presence of landward sediment deposits (Figure 2d).

Several questions about this figure: (1) Which way is seaward/ landward? (2) If seaward is to the right, why is an upward trajectory considered to be negative (2a)? (3) Where are these examples taken from?

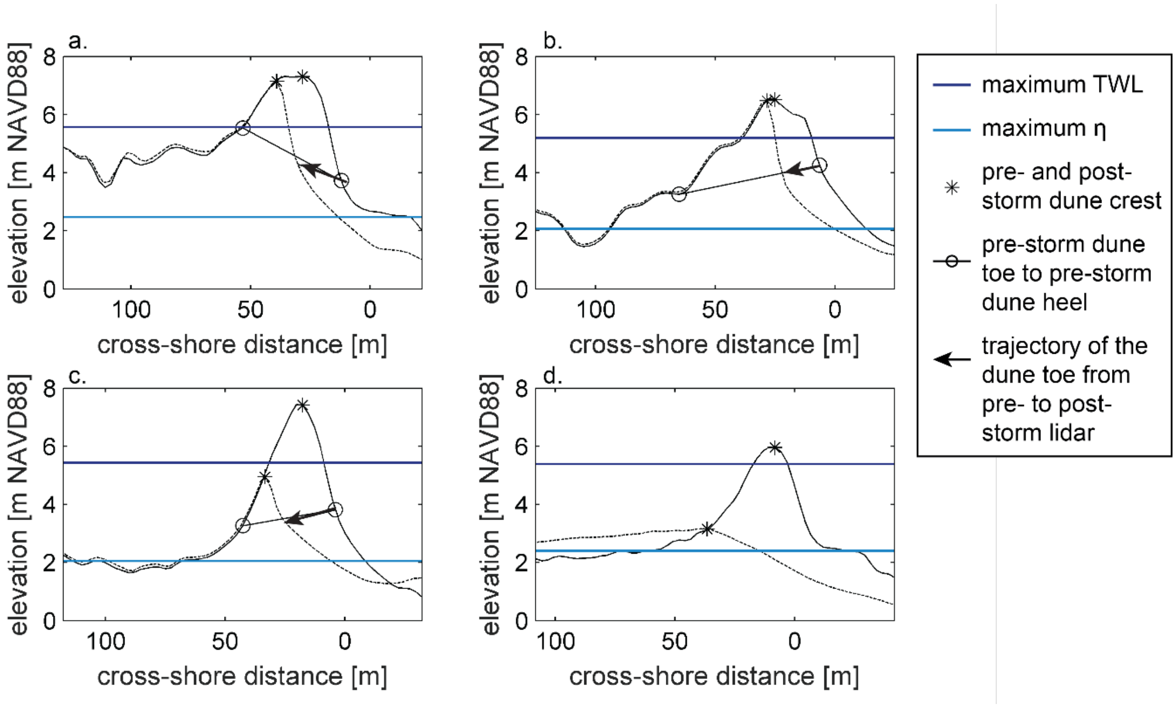


Figure 2. Example profiles expected to undergo dune erosion; high elevation back barrier (a), low elevation back barrier with no loss of crest elevation (b), low elevation back barrier with large reduction in the dune crest elevation (c), and profile that underwent overwash (d).

I don't see how -0.999 radians equals a vertical face - it seems to me that a vertical face should occur at 1.57 (pi/2) radians (90 degrees)

In general, dune erosion caused the seaward dune faces to steepen (Figure 3a), however β_D never exceeded -0.75 radians sloping in the offshore direction (β_D approaching -0.999 indicates a vertical face). On average, β_D was steepened by 43% due to dune erosion. In contrast, all of the dunes that overwashed were flattened, converging on a similar β_D (~ 0.1 radians) regardless of the pre-storm dune slope (Figure 3).

There's that misuse of "flattened" again.

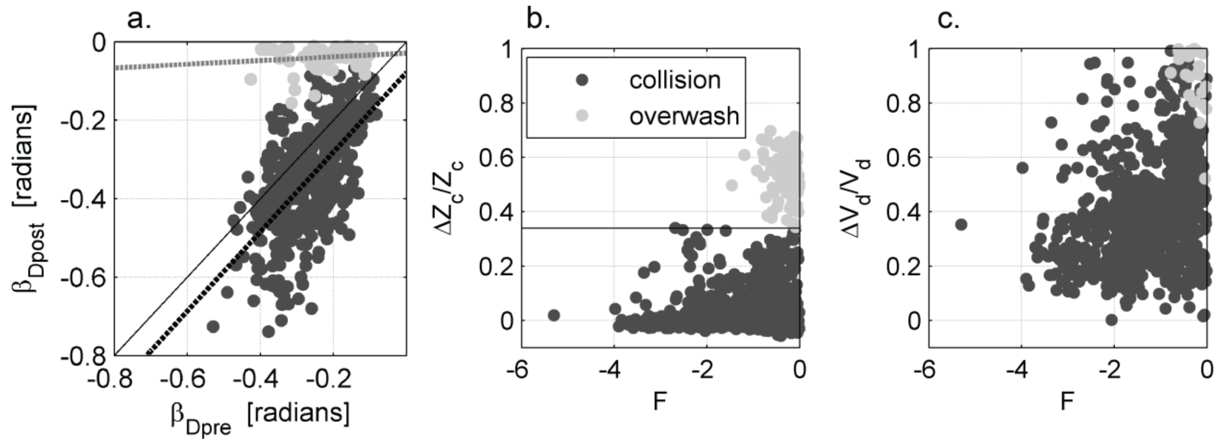


Figure 3. Pre- and post-storm dune face slope for collision (dark gray) and overwash (light gray) profiles (a). Normalized changes to the dune crest elevation (b) and dune volume (c) as a function of dune freeboard.

Is Zc measured as vertical distance above dune toe elevation? According to the definitions provided above, I don't think so and I'd have to take issue with this. Comparing the same delta Zc for dunes with different Zt would yield misleading results.

The location of the dune toe migrated landward at all profiles with both increases and decreases in elevation (Figure 4). In fact, at 50% of the profiles, the post-storm dune toe elevation was lower than the pre-storm elevation, creating a positive (downward sloping) dune toe trajectory. In cases like this, dune erosion models that relate dune toe trajectories to the foreshore beach slope by a constant factor would produce inaccurate results. For comparison, 70% of the observed dune toe trajectories had a sign consistent with an alternate formulation based on the slope between the pre-storm dune toe and dune heel, θ_H (Figure 4).

This sentence should be rewritten for clarity. I don't understand what is meant by "a sign consistent with an alternate formulation…"

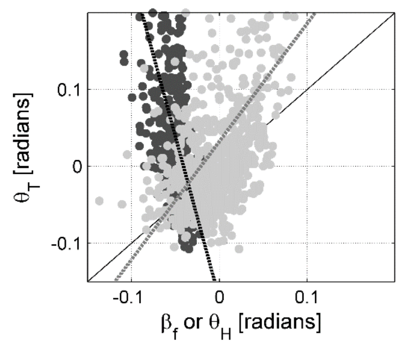


Figure 4. Foreshore beach slope (dark gray) and slope between dune toe and heel (light gray) compared to the observed dune toe trajectory.

I don't consider this to be an accurate assessment of figure 3a. The spread in normalized dune crest elev. increases as F becomes less negative.

Normalized dune crest elevation change, $\Delta Z_C/Z_C$, increased with increasing F (i.e. water levels reaching elevations closer to the dune crest; Figure 3a). Scatter was due, in part, to profiles where overwash occurred despite negative F computed using the predicted TWL; 13.3% of the profiles. The predicted TWL was within 0.5 m of the dune crest elevation at the profiles where overwash was observed. At these profiles the dune crest elevation was reduced by a maximum of 70%, significantly more than at locations where overwash was not observed. At locations where only dune erosion was observed, more than 80% of the profiles had dune crest elevation changes of less than 10% with a maximum observed change of 34%.

Explain how this happens.

How did you observe overwash?

Is this meant to say "where only dune collision was observed"? Basically an assessment of the information presented in Fig. 3b?

Similar to the changes in dune crest elevations, eroded dune volumes also increased with increasing F, however, much more scatter was observed (Figure 3b). At 95% of the locations where dune erosion was expected, dunes lost at least 14% of their original volume; however in some locations maximum observed losses reached 100% of the dune volume above the dune toe. In comparison, 95% of dunes where overwash occurred lost 81% or more of their pre-storm

Figure 3c?

dune collision?

volume. Along these profiles the sediment lost was either transported offshore or landward creating an overwash deposit, which was no longer considered part of the dune.

5 Discussion

5.1 Implications for modeling

We compared observations of dune behavior to assumptions of dune toe trajectory and dune face slope in wave-impact models [*Larson* et al., 2004; *Palmsten and Holman*, 2012; *Splinter and Palmsten*, 2012]. Additionally, process-based models like XBeach and SBEACH require β_D as a user-defined input [*Larson* et al., 1990; *Roelvink* et al., 2009]; however, without widely observed or published values, the default is often a vertical β_D [*Larson* et al., 2004; *Palmsten and Holman*, 2012; *Splinter and Palmsten*, 2012]. With this assumption, the stability of the dune crest and resistance to erosion can be over-estimated. In wave impact models in particular, eroded sediment volume is computed at each time step assuming a vertical front face and a dune toe trajectory that follows the foreshore beach slope. Incorrectly specifying these parameters will lead to erroneous predictions. Although dunes did not reach a vertical β_D, scarping was observed and caused an overall steepening of β_D. On average, dunes in this study were found to erode to a 43% steeper slope than the pre-storm β_D; a condition-specific proportional constraint that could be applied to these models.

Wave-impact dune erosion models also depend on specification of a constant trajectory of the dune toe (θ_T) [*Erickson* et al., 2007; *Larson* et al., 2004; *Palmsten and Holman*, 2012; *Splinter and Palmsten*, 2012]. The difference between a positive and negative value of θ_T has serious implications for not only how long waves erode the dune, but also the potential amount of sediment available to be eroded. If θ_T is assumed to be the foreshore beach slope, the potential for dune erosion during a storm decreases, as the toe always marches upwards and potentially above wave-impact. 50% of the dunes analyzed were found to erode along a slope opposite of the foreshore beach slope (linear regression slope of -4.22), translating the dune base inland and to lower elevations. This may increase the vulnerability to additional dune erosion throughout the duration of the storm. A higher percentage of the observed θ_T were of the same sign as θ_H (70%) and a linear regression slope closer to one (1.54).

Could the authors comment on the implications of this observation?

The large multi-state region of which dunes were analyzed and the diversity of dune response documented after Hurricane Sandy contribute robust estimates of β_D and θ_T. Previous experiments used high elevation dune heels in their lab-based experimentation of dune erosion [*Palmsten and Holman*, 2012; *Erickson* et al., 2007] or a limited number of field profiles. This work incorporates a much broader dataset for identification of model parameters.

5.2 Variability in dune crest erosion

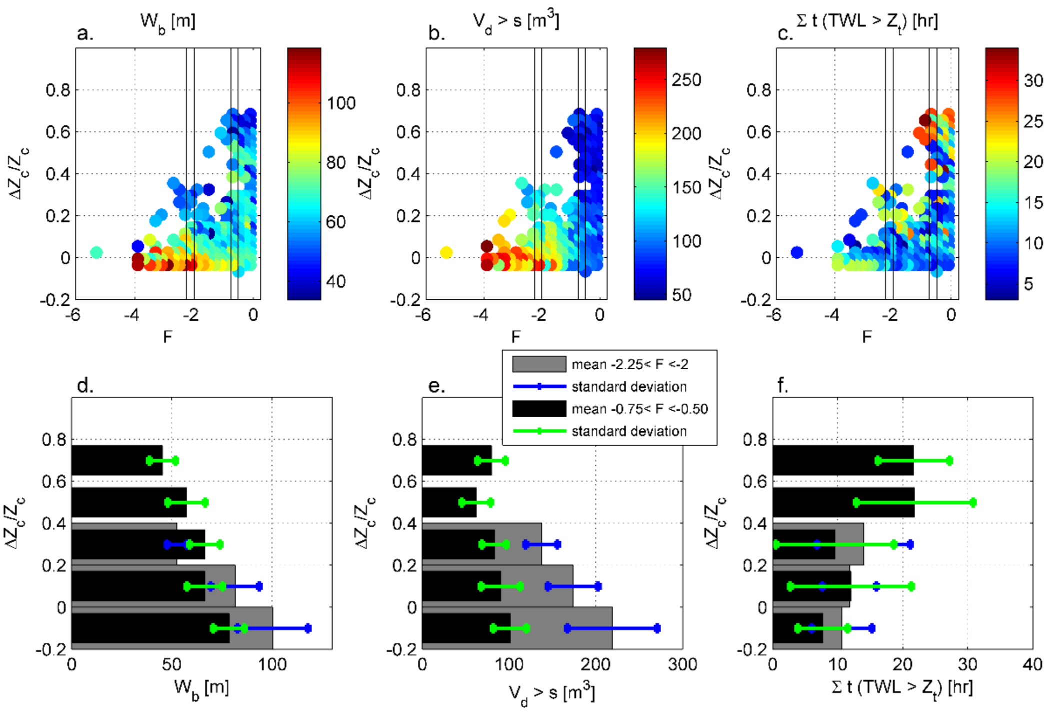
On average, dune elevations did not change significantly at the profiles analyzed here; the average change to Z_C was only 4% of the pre-storm dune elevation. However, there was significant alongshore variability in the response, including some dunes that eroded to the point where overwash occurred. Comparisons shown here indicate that, at profiles with the same dune freeboard, the dune response can vary significantly (see, for example, values plotted between black vertical lines; Figure 5a-c). The general response is described by binned values for $\Delta Z/Z_c$ (0.2 m/m bins) along with the average and standard deviation for each bin (Figure 5d-f).This response could be, in part, the result of variability in beach and dune characteristics or the amount of time a dune face is exposed to storm conditions. We investigated how the differences in dune crest elevation change compared to variability in the beach width (W_B), dune volume above surge elevation ($V_D > s$), and the wave-impact hours (integrated time that the TWL time series exceeded the dune toe).

As observed by Plant and Stockdon [2012], there was an increase in dune crest elevation change with decreasing beach width suggesting that dunes fronted with narrow beaches are more vulnerable to dune erosion than those fronted by wide beaches (Figure 5a & d). This increased erosion can lead to larger reductions in dune crest elevation, not just increased eroded volume, and any decrease in dune crest elevation can increase the vulnerability of erosion and flooding during future events. This is particularly important because existing dune erosion models are often validated using flume experiments calibrated according to changes in the dune toe with little emphasis on changes to the dune crest elevation [*Erickson* et al., 2007; *Larson* et al., 2004; *Palmsten and Holman*, 2012].

The degree to which differences in erosion can be attributed to variability in the volume of dune sediment above the surge level was also tested. This parameter provides an indication of how much material must be eroded before water levels can reach the back barrier. Given similar dune freeboard, the dunes with larger sediment volume above surge elevations were found to be more resistant to changes in dune crest elevation (Figure 5b & e). Hence, as might be expected, narrow dunes are more likely to be eroded faster and decrease in elevation. Storm duration is also an important indicator of coastal change, which for the data analyzed here, was quantified using the number of hours where wave-impact exceeded Z_T. Results indicate that erosion of the dune crest

Perhaps the authors might consider substituting “dune crest lowering” for “erosion of the dune crest”?

increased with increasing wave-impact hours, however, variability about the mean was higher for wave-impact compared to beach width or dune volume above surge (Figure 5).



This coloring scheme needs to be better explained.

Figure 5. (Top row) Normalized changes to the dune crest as a function of dune freeboard, colored by the mean value, of dune width (a), dune volume above surge (b), and wave-impact hours (c). (Bottom row) Mean and +/- one standard deviation for values of similar dune freeboard between the black vertical line segments (a-c) binned in 0.2 m/m intervals.

6 Conclusions

Cross-shore profiles at 861 individual locations from Maryland, New Jersey, and New York were analyzed to quantify dune erosion during Hurricane Sandy. The profiles spanned a wide range of geomorphic conditions and allowed for testing parameters that control dune evolution in wave-impact dune erosion models. They also help inform other simplified scaling models [*Long* et al., 2014, *Stockdon* et al., 2007] and more complex modeling approaches (e.g. *Roelvink* et al. [2009]).

The slope of the dune face as the dune erodes is a parameter which is generally unknown, has little guidance provided from previous studies, and is often assumed to be vertical. No dunes were found to erode to a vertical front face from Hurricane Sandy, but instead, on average, to 43% steeper than the pre-storm slope. Erosion of the dune toe was more likely to follow a trajectory towards the dune heel elevations (70% of the time), rather than the foreshore beach slope (50% of the time). A positive (downward) dune toe trajectory and non-vertical dune face increases the potential amount of sediment available for erosion and changes the final dune crest elevations in dune erosion models.

Not sure this positive/downward convention is consistent with other gradient calculations in geomorphology.

word order?

The vulnerability of the coastline increased to future storms because of reductions to dune volumes, which was on average 41%. Narrow beach widths, small dune volumes above maximum surge elevations, and high wave-impact hours above the dune toe elevation throughout the duration of the storm contributed to greater magnitudes of coastal change. Dune erosion models have the potential to be improved by applying the measured changes to dune morphology analyzed here.

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trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. Data can be made available upon request to the corresponding author (jacquelyn.overbeck@alaska.gov).

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